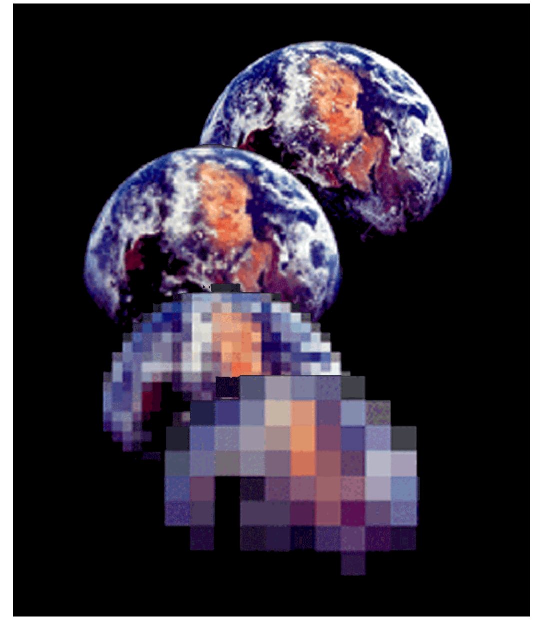
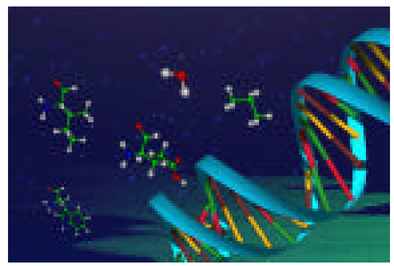
NASA's Interferometry Program: The Search for Life Beyond the Solar System

Some Facts and Figures



Planet Imaging



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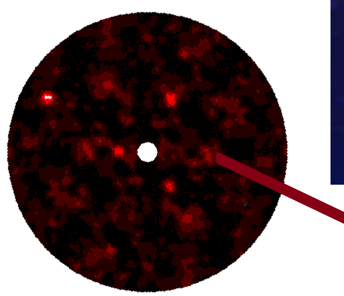
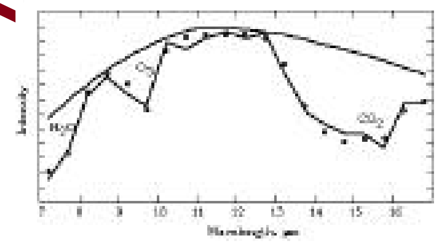
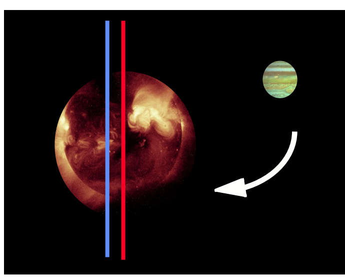


Family Portrait





Indirect Detection

Prepared for the Administrator

June 16, 1997

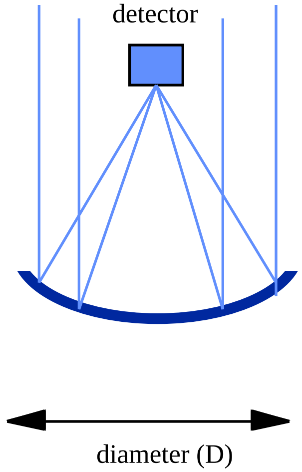
What is in this Package?

A Primer on Interferometry Technology, Science and Missions

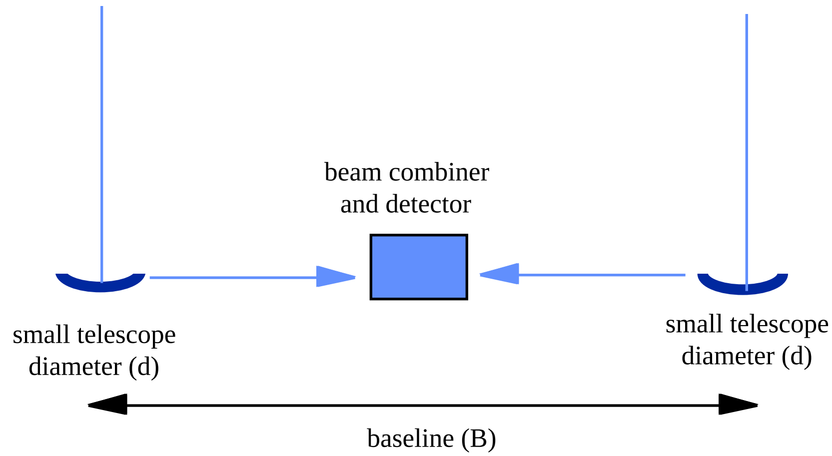
- How do interferometers work in different modes? (pages 3-6)
  - Imaging
  - Astrometry
  - Nulling
- What is the precision required to make an interferometer work? (pages 7-9)
  - Path length control
  - Path length knowledge
- How will NASA use interferometry in future missions? (pages 10-18)
  - What are the scientific or technology goals of each mission?
  - What are the precision requirements in each mission
- How can we detect planets around nearby stars? (pages 19-23)
  - Directly using Terrestrial Planet Finder
  - Indirectly with the Keck and SIM interferometers via astrometry
  - Indirectly using NASA time on Keck-I via radial velocities

Telescopes vs. Interferometers

Telescope



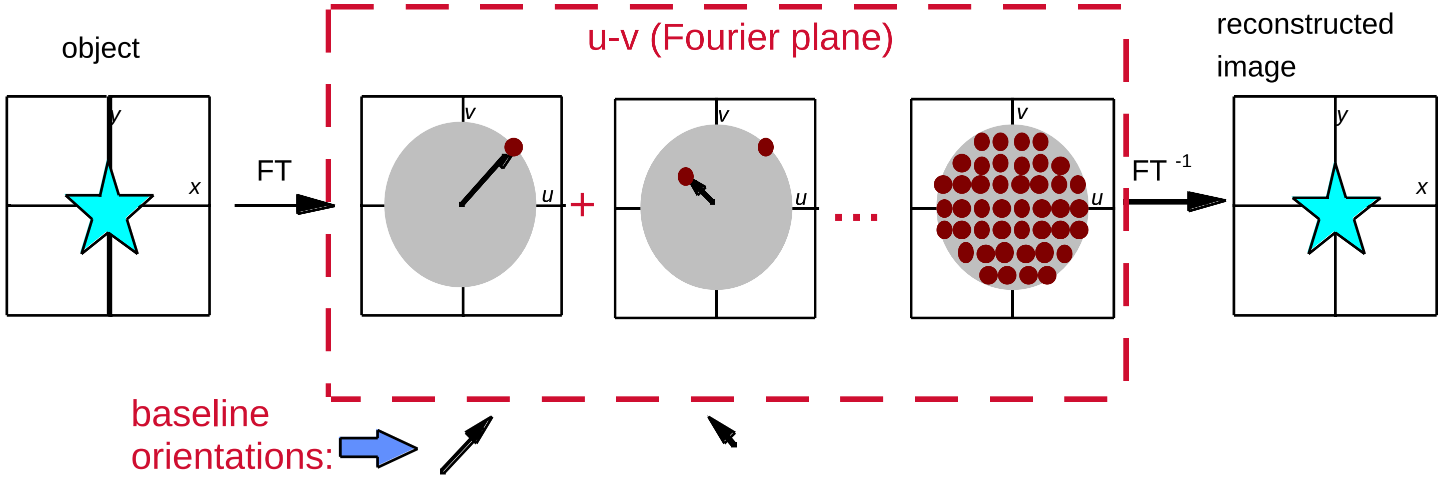
Interferometer



Relative to a telescope, an interferometer has a much higher resolution but in a smaller field of view

Examples	Imaging Resolution (ability to see fine details)	Field of View
 D=2.4m d=N/A B:=N/A λ=0.5μm HST	**λ/D** = 0.5 μm/2.4 m =0.21 micro radian = 0.04 arcsecond	Large: 2.7 arcminutes (1600pixels*0.1arcsec/pixel) primarily set by the size of the detector array
 D=N/A d=0.3m B=10m λ=0.5μm SIM	**λ/B** = 0.5 μm/10 m =0.05 micro radian = 0.01 arcsecond	Small: Approx. 1.0 arcsecond set by λ/d

Imaging with an Interferometer

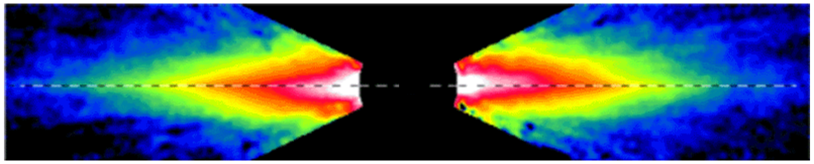


Synthesis Imaging

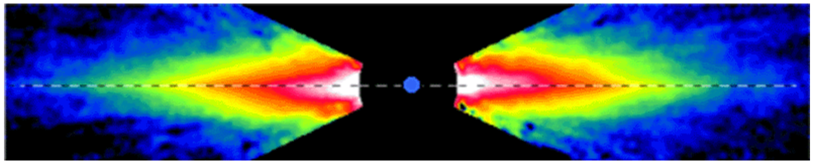
- Unlike telescopes which image objects directly, interferometers measure the Fourier transform of the object which is then inverted to get the image
- Data in the Fourier plane is built up one point at a time
- Each baseline orientation selects a point in the Fourier plane at which the interferometer measures fringe visibility and phase
- Rotating the interferometer results in a ring of points in the Fourier plane
- Filling the plane requires either shrinking and expanding the baseline or having multiple telescopes on the baseline structure (which, in effect, gives us multiple interferometers of various baselines) to get points at different radii
- Number of required points varies depending on object complexity
- With SIM, imaging an object using this technique takes several hours

Starlight Nulling -- How Is It Done and Why?

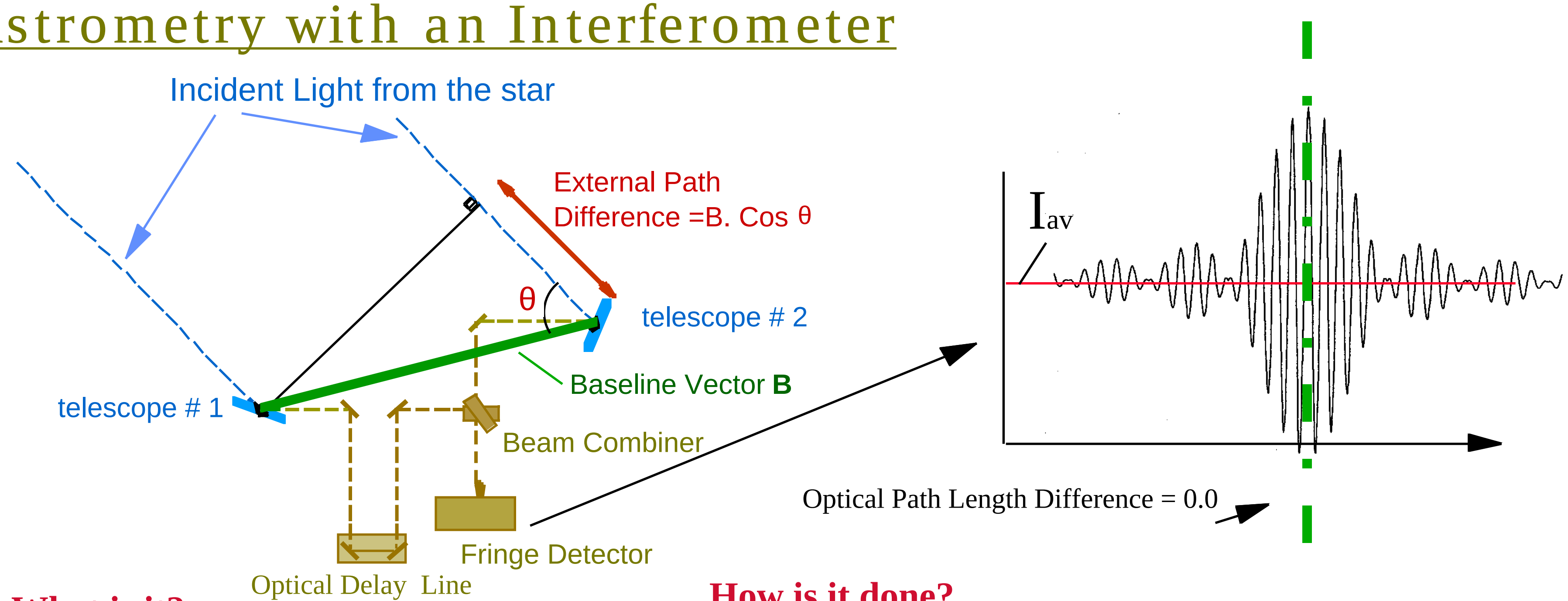
- To study faint objects, such as planets and zodiacal dust in the vicinity of a bright star, the starlight must be greatly reduced (nulled) so that it does not overpower the much dimmer objects around it.
- A nulling interferometer uses a beam combiner which combines the light from the two arms of the interferometer so that the on-axis light is nulled.
- This is an image of the star Beta Pictoris taken by the Hubble Space Telescope. The dark area is the region blocked out by the HST so that the outer regions of the dust disk around the star can be viewed. The blocked-out region is 3-4 arcseconds across; no information is available within this area.



- An interferometer looking at the inner reaches of the zodiacal clouds or searching for planets in the habitable zone needs to do a much tighter null (spatially) to make sure that it blocks only the star but not its vicinity where we are searching for interesting objects. The dot in the center of the picture below shows how the nulling done by SIM will compare with HST.



Astrometry with an Interferometer



What is it?

- Astrometry is the science of pinpointing objects in the heavens and measuring their motions
- In an interferometer, the light from a star arrives at one of the two telescopes sooner than the other thus creating an external path delay x
- Angle θ is the angle between the stellar wave front and the interferometer baseline **B**
- If we know vector **B**, and can determine x, we can solve for θ and therefore determine the relative position of the star

How is it done?

- We determine the external delay by introducing an internal delay which exactly matches it.
- This is done by introducing in one arm of the interferometer an optical delay line which is adjusted until the internal delay matches the external delay.
- How do we know we have accomplished the exact match?
  - Light from the two telescopes are combined in a beam combiner and sent to a detector.
  - When we are not close to an exact match, the detector measures an average intensity (I_{av}) As we get closer, fringes appear. Using an algorithm that looks at the fringe and feedbacks to the delay line, we keep adjusting the delay line until we are at the peak of the fringe -- now we have an exact match.

Mind-numbing Numbers

- For all its capability, an interferometer also presents formidable technological challenges. Relative to the discussion of the previous page, with a 10m baseline interferometer, if one wants to measure position of a star to a 1.0 micro arcsecond accuracy (i.e determine t to within 1 μas), then one needs to know vector B to an accuracy of 50 picometer and, to get clean fringes, one needs an optical delay line with a 10 nanometer path length control.

- These are mind-numbing numbers: Here is a good way to visualize what these numbers mean:

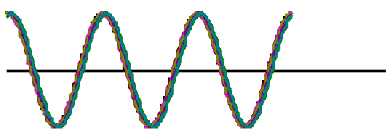
  - picometer -- that is the 1/100 dimension of a hydrogen atom!!
  - nanometer - - a very small fraction of the thickness of your hair
  - micro arcsecond - - If a man was standing on the surface of Mars with a flashlight in one hand and he transfers it from one hand to the other............if you can detect that, then you have ability the detect angles in the heavens with 1 μas resolution

- While these numbers are amazing, even more amazing is the fact that NASA is in a position to pull it off!

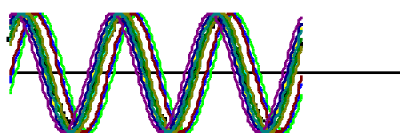
Requirement on Path Length Control -- What Drives It?

- Vibrations result in path length fluctuations which blur out the fringe, making it hard to detect
  - Need real-time control of path length equal to $\lambda/50$
    - For SIM that is $0.5\mu m/50 = 10nm$
    - For TPF that is $10\mu m/50 = 200nm$

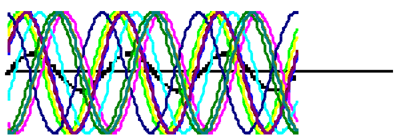
Fringe visibility under various path length control regimes for SIM



10 nm rms



50 nm rms



200 nm rms

- For nulling the starlight, the required path-length fluctuations (σ) need to be even smaller

$$\sigma = (\lambda/2\pi) \times (\mathrm{sqrt}(\text{null depth}))$$

For TPF where λ is $7\ \mu m$ and the desired null depth is 10^{-6}, σ is approx 1nm

Requirement on Path Length Knowledge -- What Drives It?

- For astrometry, path length knowledge is tied to the desired astrometric accuracy
  - The SIM requirement for *narrow angle* astrometry is 1 micro arcsecond (µas) or 5 picoradian
  - With a 10m baseline this corresponds to 10m x 5 picoradian = 50 picometer requirements on the path length knowledge.
  - Note that the larger the baseline, the more relaxed the requirement on path length knowledge
  - Conversely, a better knowledge of path length results in improved astrometric accuracy for a given baseline.

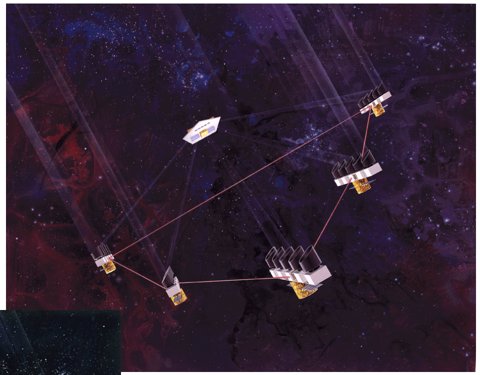
  Example
  - A single Earth-mass planet in an Earth-like orbit around a solar-mass star at a distance of 10 parsec (33 light years) will cause the star to wobble by 0.33 µas
  - From the above, starting with the reference point of 1µas astrometry needing a 10m baseline and 50 picometer path length knowledge, we come to the conclusion that SIM can detect this planet if:
    - We improve our knowledge requirement by a factor of 3 (1µas/0.33µas) from 50 to 17 picometers
    - or, by increasing its baseline by a factor of three from 10 to 30 meters
    - or, detect the same planet if it were a factor of 3 closer to us so that the wobble signature would be 1 rather than 0.33 µas

- For imaging, rather than astrometry, the path length knowledge requirement is considerably more relaxed

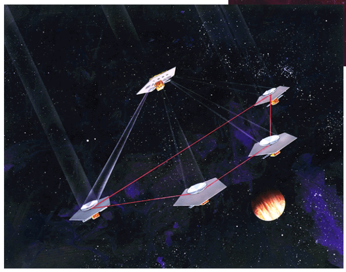
NASA’s Interferometers:

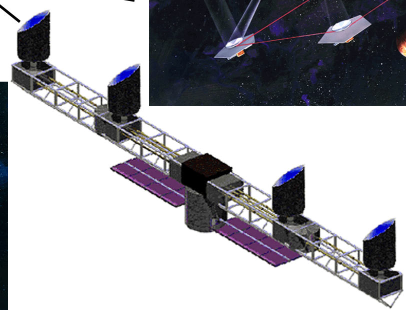
Under Development, On the Drawing Board, and Over the Horizon

Planet Imager --2020??

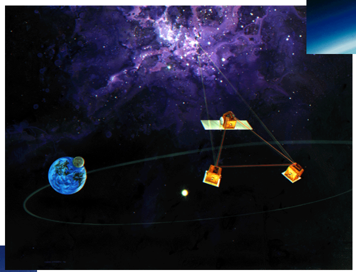


Terrestrial Planet Finder (TPF) -- 2010

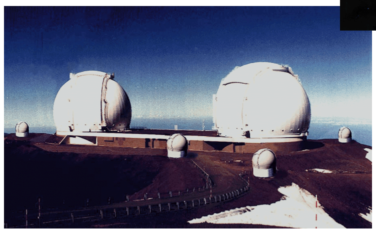




Space Interferometry Mission (SIM) -- 2005



New Millennium Program DS-3 Interferometer -- 2001



Keck Interferometer -- 2000/2001

Astrometry -- Ground vs. Space

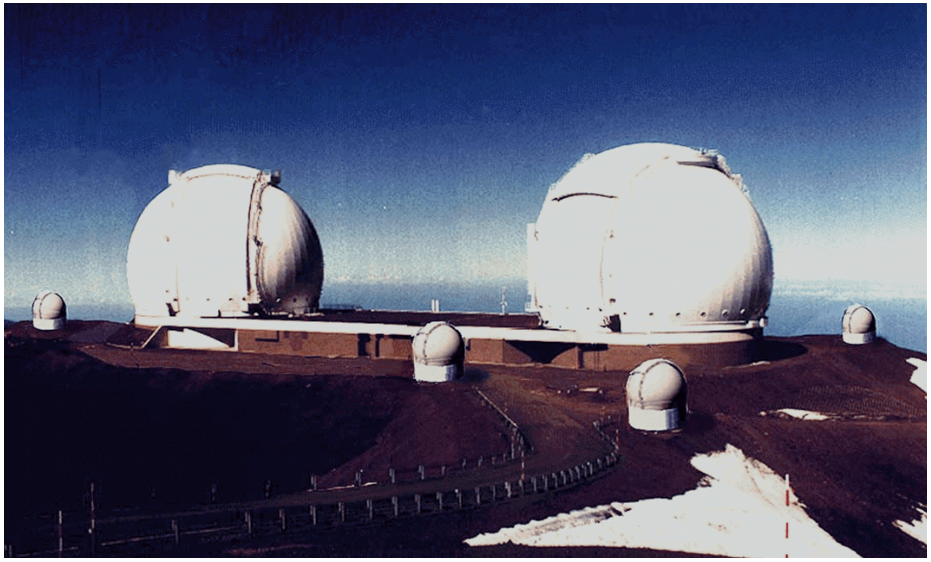
- Precision astrometry from the ground (Keck interferometer)
  - Inherently narrow-angle
    - Works in small field of view defined by coherence size of the atmosphere
      - The iso-planatic patch is about 20 arcsec at 2 μm
    - Method requires ≥ 2 reference stars within iso-planatic patch
    - Fundamental limit of ~10 μas set by atmosphere
    - Integration time of ~1 hour to reach 10 μas astrometric accuracy

- Precision Astrometry from Space (SIM)
  - Works over the entire sky (4π) enabling a broad range of astrophysics
  - Limit of 4 μas (wide-angle) or 1 μas (narrow angle) set by instrument
  - Integration time of ~1 minute to reach 10 μas for bright star

Keck Interferometer

Salient Features

- The two 10m Keck telescopes + four to five 2m outrigger telescopes
- 85-meter baseline between the two Kecks
- λ: 2 μm and 10 μm
- Imaging resolution: 5 milliarcsecond at 2 μm
- Astrometric accuracy: 10 μas



Science

- Direct detection of brown dwarfs and warm Jupiters (Jupiter-mass planets in close orbits)
- Null the star and study zodiacal clouds around the nearby stars
  - This data is needed for the TPF design
  - The intensity of these clouds and the structure within it (local clumpiness that may masquerade as planets) have a strong influence on the size of Planet Finder telescopes and the longest baseline between them -- long baselines favor formation flight
- Indirect detection of many Uranus-size planets via astrometry
- High resolution imaging of disks in which planets may be forming

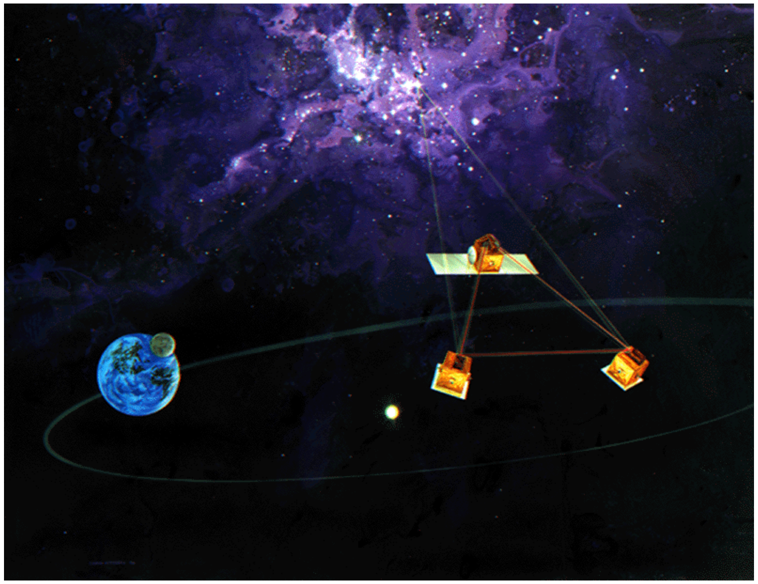
The first two objectives can be met with only the two Kecks connected as an interferometer.

The next two require the additional baselines provided by the outrigger telescopes

DS-3 Interferometer

Salient Features

- Three s/c flying in formation -- 1cm precision
- 1 to 10 km baseline
- λ -- Optical
- Imaging resolution: 100 μas (at 1 km) ;
  10 μas (at 10 km)



Technology

- Very long baseline optical interferometry -- applicable to TPF
- Space validation of many H/W and S/W elements for SIM

Science (not primary objective of the mission)

- Tidal distortion of a star's photosphere due to a black hole orbiting the star

Space Interferometry Mission (SIM)

Salient Features

- 10m Baseline
- λ: Optical
- Path Length Control: Nanometer class.
- Path Length Knowledge:Picometer class
- Imaging Resolution: 10 milliarcsecond
- Astrometric Accuracy: 4 μas wide angle; 1 μas narrow angle

·High priority mission by the last astrophysics decadal report (John Bahcall). Reconfirmed by the recently concluded National Academy mid-decadal report

Science

- Indirect detection of planets outside the solar system through observation of thousands of stars
- Improve on the best current catalog on star positions within our Galaxy by a factor of 250 and extend the sensitivity to much fainter stars. Using this data SIM can probe the spiral structure of our Galaxy and measure the mass of its halo -- a relic of the Galaxy formation
- Studying structure of planetary dust disks using starllight nulling imaging
- Very high resolution (10 milliarcsecond) imaging of broad range of astrophysical phenomena

Technology

- SIM will be the world's first spaceborne operational long-baseline optical interferometer
- As co-equal objective to its science, SIM is also to be a technological pathfinder to the Terrestrial Planet Finder (TPF) mission

Expanding on SIM Science

How Sensitive is SIM?

- How long does it take to see the stars move? Using the unaided human eye with a resolution of 1 arcmin, we would have to wait 6 years for the proper motion of Barnard's star to be detectable. (Barnard's star has the largest proper motion of any object outside the solar system.) With the Hubble telescope and the Hipparcos satellite (1 milliarcsec) astrometric accuracy, we would have to wait just one hour. With SIM, we would see that motion in just 15 sec. This astrometric accuracy enables a wealth of new information about our Universe.

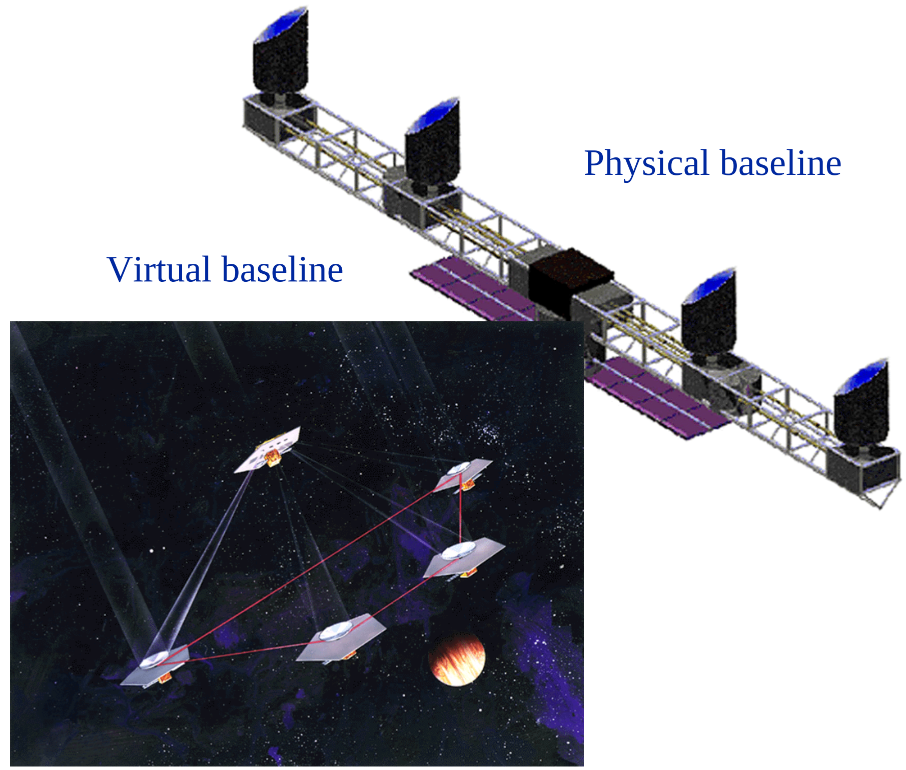
Planet Detection

- Exhaustive search for exo-planets around nearby stars: SIM using ~20% of its time can search ~20,000 nearby stars for gas giant planets (10 Earth masses) out to a distance of 50 parsec. A jupiter-mass planet around a Sun can be detected at a distance of 2 kiloparsec (a volume of space that contains ~ a billion stars). SIM will also be able to search for Earth-mass planets around a small number of very nearby stars (~50).

The Age of the Universe

- The age of the Universe as determined by the value of the Hubble constant is paradoxically less than the age of the oldest stars in globular clusters. SIM will shed light on both ends of the question: 1) by measuring more accurately the age of stars in Globulars and 2) by measuring the Hubble constant more accurately.
  - In studying globular clusters, SIM will be able to not only measure their distance (and hence luminosity and age), but by measuring their motion around the galactic center, deduce the amount of "dark" matter in the halo of our galaxy.
  - The Hubble constant is derived from a large number of indirect distance measurements. One of the critical ones is the calibration of the Cepheid period-luminosity relation. SIM will be able to directly measure the distance to cepheids in our galaxy as well as in nearby galaxies

Terrestrial Planet Finder (TPF)



Salient Features

- Baseline 75-100m (physical) or more (virtual)
- Telescope size: 1.5 meters if operated at 5AU >5m if operated closer to Earth (to offset higher background noise from the local zodiacal dust)
- λ: 7- 17 μm
- Path Length Control: 1 nm
- Path Length Knowledge: <1nm
- Imaging Resolution: < 25 milliarcsecond

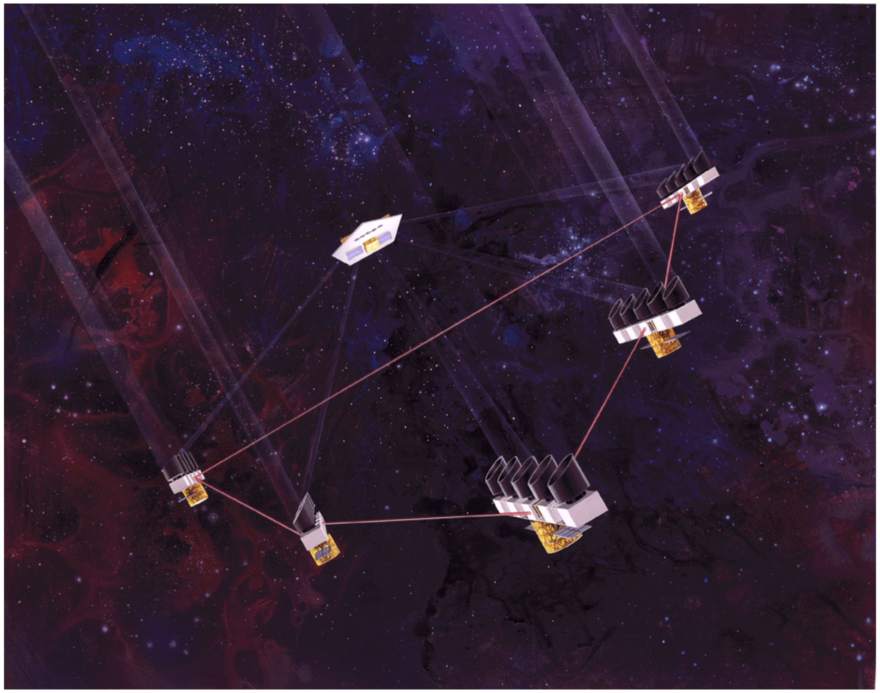
Science

- Obtaining a family portrait of the planets revolving around nearby stars
  - Examine 1000 of our closest stars (40 light year radius)
  - Null the starlight to image the planets
- Spectroscopic analysis of the detected light from the planets
  - Look for atmospheric composition that may indicate habitability ... or even the presence of life itself.

Planet Imager

Salient Features

- An array of TPF class interferometers flying in formation
- Starlight nulled at each interferometer and relayed to a beam combiner S/C
- Each interferometer carries four 8m telescopes to collect starlight and one 8m telescope to relay collected light to the beam combiner S/C
- Total array baseline: 6000 km
- Total light collecting area 1000 square meters



Science

- Humanity's first image of another world

Interferometer Missions -- Parameter Summary

Missions	Baseline	Wavelength	Imaging Resolution	Astrometry Accuracy	Path Length Knowledge	Path Length Control	Formation Flight
Keck Inter.	85m	2μm & 10μm	5 mas	10μas (narrow angle)	< 5nm	10nm	N/A
DS-3	1-10km	Optical	0.01 mas	N/A	< 10nm	10nm	Yes
SIM	10m	Optical	10mas	4μas (Wide Angle) 1μas (Narrow Angle)	200 pm (Wide Angle) 50 pm (Narrow Angle)	10 nm (Astrometry) 1nm (Nulling)	No
TPF	100m	7-17 μm	25 mas	N/A	< 1nm	1nm (Nulling)	Maybe
PI	6000km	7-17μm	0.0003mas	N/A	< 1nm	1nm (Nulling)	Yes

Long Baseline Optical Interferometry Expertise Around the Country

- Interferometry expertise around the world is very limited
- There are four teams in the US that have built, or are building long-baseline interferometers
  - JPL/Caltech : Palomar (110 m baseline -- fastest development from start to first fringe), Keck, SIM -- NASA funded
  - USNO/NRL: Prototype optical interferometer NPOI, in Flagstaff, Az 400m Baseline; 3 elements operational (6 funded); -- DOD funded
  - SAO/U. Wyo/UMass: Infrared Optical Telescope Array (IOTA), two 50cm telescopes 35m baseline -- Smithsonian
  - Georgia State Univ.: CHARA Array, Mt.Wilson, Ca, 5 element 300m baseline -- funded by NSF & State of Georgia

- Groups working on related areas:
  - Air Force/Phillips Lab: Lab experiments and studies of phased arrays; no current plan to build an observatory

How Does One Detect Planets?

Directly

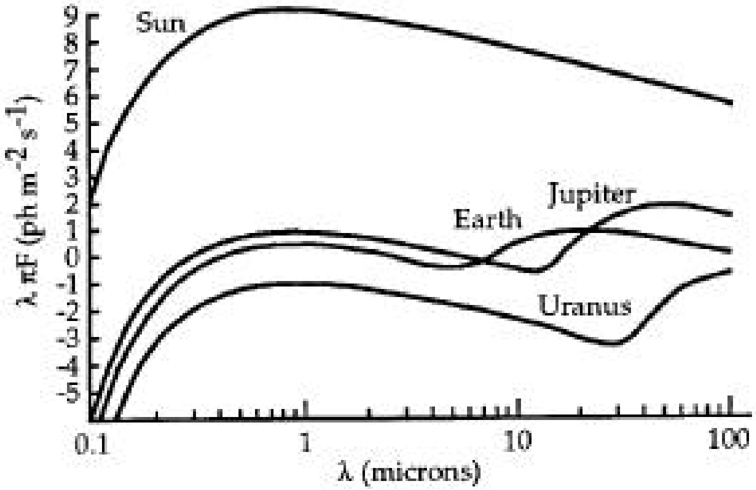
- *Direct detection* measures photons emitted from the planet
  - Null starlight to reveal planetary systems
  - Derive basic properties of planets
  - Search for signs of life

Indirectly

- A planet exerts gravitational forces on its parent star, perturbing the star's position and velocity
  - These perturbations point to presence of the planet
  - The signature of the perturbation tells us about the planet's mass and orbit

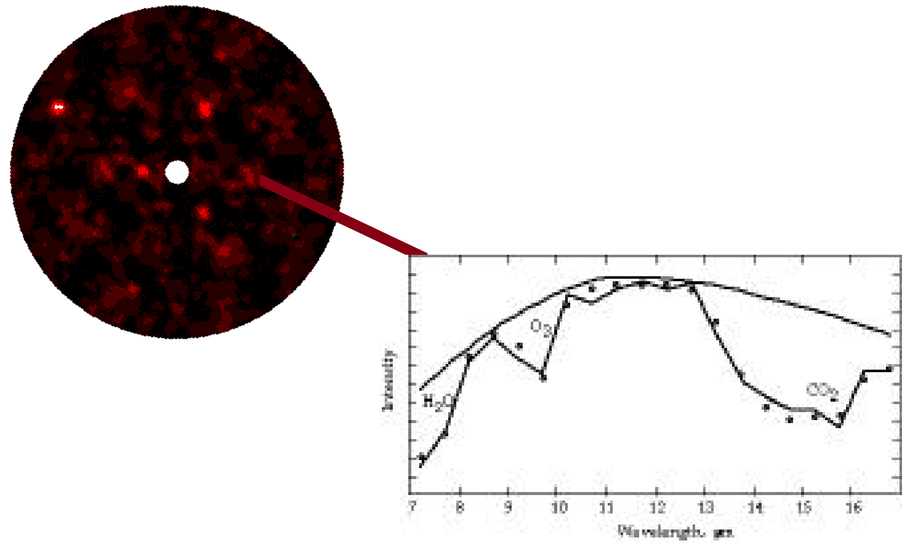
Direct Detection of Planets

- Starlight needs to be greatly reduced (by a factor of 10^6 in IR, 10^9 in visible) to be able to see the dim planet.



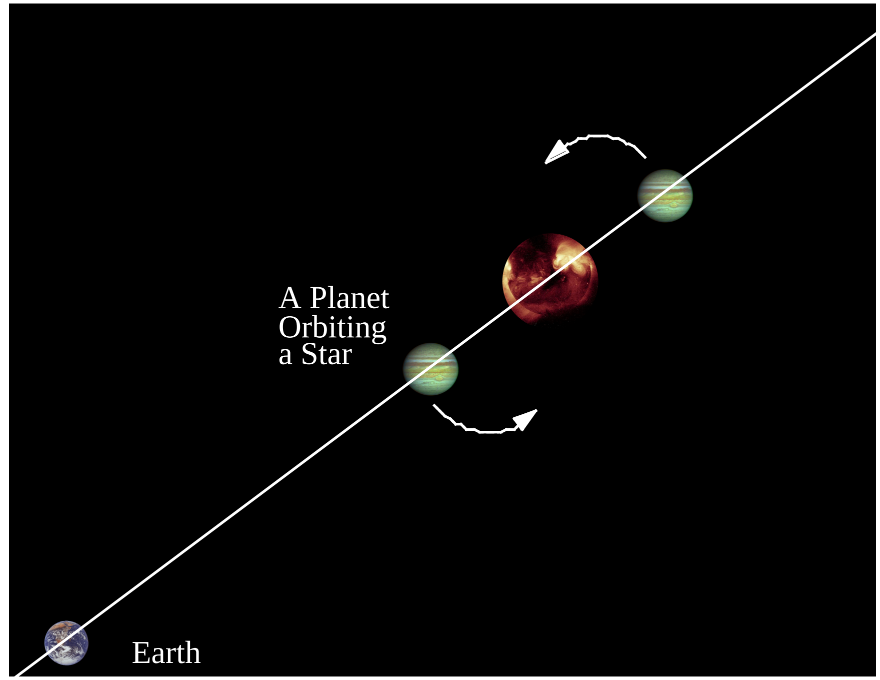
- Broad-band family portrait gives information on temperature, albedo, radius and orbital location of planet

- Spectroscopy gives chemical composition of planetary atmospheres and allows a search for telltale signs of life.



Indirect Detection -- The Radial Velocity Technique

- Gravitational pull of the planet on the star causes a Doppler shift in the line-of-sight radial velocity of the star as viewed from the earth.
- Looking at the spectrum of the star light, one would note a periodic shift of the spectral lines toward the red and then toward the blue. The period of this shift is the planet's orbital period.
- The strength of the radial velocity perturbation increases for larger planets closer in. That is why most of the planets detected so far are Jupiter-class planets in orbits far closer (sometimes dramatically closer) than our Jupiter's orbit around our Sun.



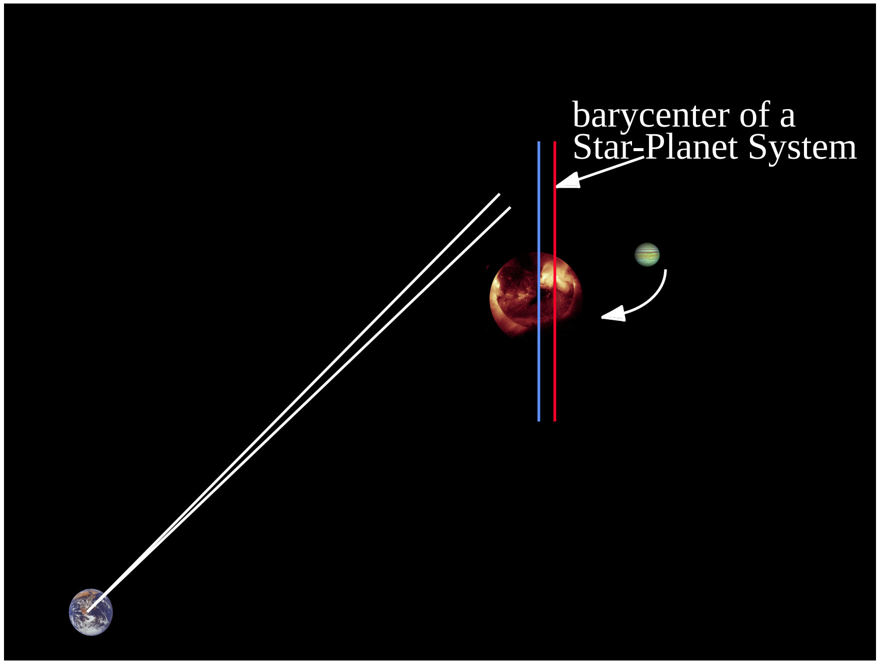
- The Controversy: One of the planets detected is a Jupiter-class planet with a four-day orbit around the star 51Peg.
- Some have claimed that the observed change in radial velocity could be due to oscillations in the star's atmosphere and not to a planet.
- Our Sun's atmosphere has such motions with period of hours.
- This controversy does not affect detected planets with much larger orbits.

Indirect Detection -- The Astrometric Technique

- In a planetary system, both the planet and the star orbit about the barycenter of the star-planet system. This makes the star's position appear to wobble.

- Precise measurement of the position of the star (called *astrometry*) tells us the extent of the wobble from which we can deduce the planet's mass and orbit

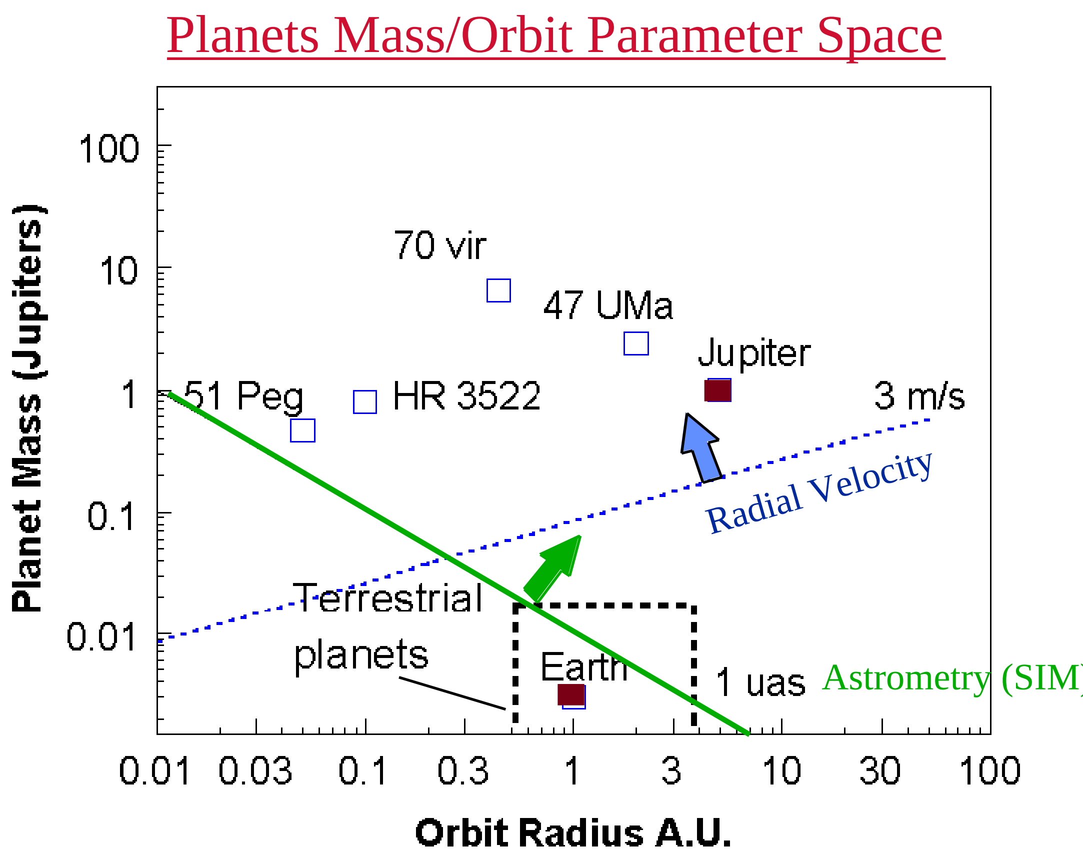
- The magnitude of the wobble increases for larger planets orbiting farther from the star (because it moves the barycenter farther away from the center of the star which in turn increases the wobble)



- An earth-mass planet orbiting in an earth-like orbit around a solar-mass star 33 light years from us will produce 0.3 μas wobble in the star's position
- Jupiter with 300 times the mass of the Earth and 5 times its orbital distance, produces a signature 1500 times as strong -- 500 μas.

Planet Detection -- Radial Velocity vs. Astrometric Technique

- Radial Velocity technique can be expected to reasonably detect planets with more than 3m/s signature -- these are large planets.
- SIM using Astrometric technique can get very close to terrestrial planets -- the interesting planets in the habitable zone.



- The chart above shows some of the recently detected planets (Jupiter and Earth are shown for reference) using radial velocity technique.
- The 3m/s is a reasonable threshhold of what can be done with the radial velocity technique (note that all the detected planets lie above this line). The 1μas line is the SIM detection capability using astrometry.